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A Spatial Approach

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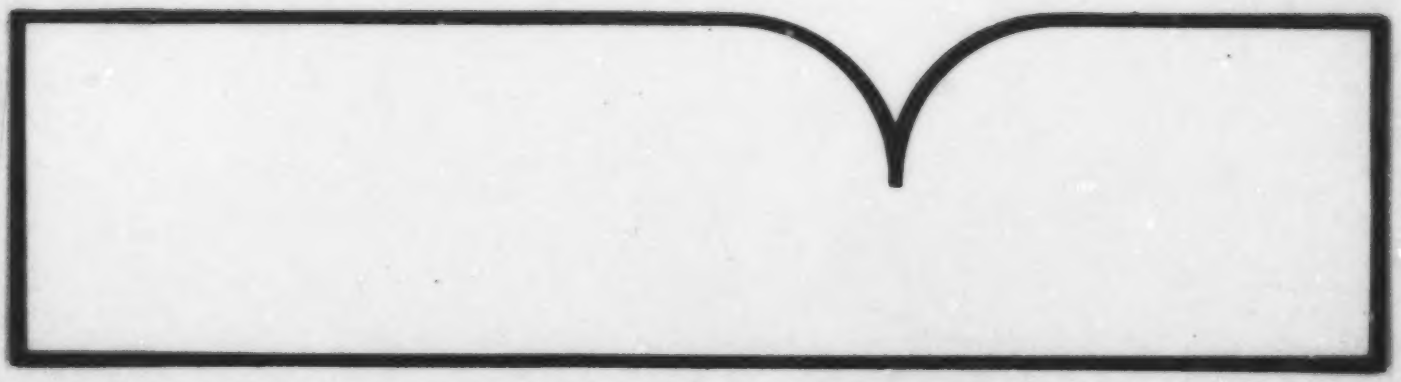

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ANALYSIS OF DRINKING WATER SYSTEMS: A SPATIAL APPROACH

by

Robert M. Clark M.ASCE[a] and James A. Goodrich[b]

ABSTRACT: There has been a growing interest and awareness of the use of spatial analysis in water supply engineering. Normally, spatial location and relationships have been considered incidental, although many engineering activites dealt with the design, construction and provision of services over geographically diverse locations. This paper describes recent examples of spatial analyses as (1) a unifying concept for allocation of costs to various elements of water treatment and delivery (2) a link and node (Network) representation of water supply being integrated with the Water Supply Simulation Model and maintenance and pipe replacement data to provide a tool for analyzing "break and leak reports" and (3) to predict water quality at various locations in a water distribution system. Another far reaching example of spatial analysis in water supply is the integration of upstream industrial and toxic dischargers with design decisions in downstream water treatment.

INTRODUCTION

Many of the subdisciplines of Civil Engineering deal with locating, planning and designing, and analyzing mans' activities. For example, transportation, surveying, construction hydraulics, and environmental engineering are in some way involved with the location of population centers, their characteristics, and are the consequences of mans' activities. Much of civil engineering is involved in building the infrastructure that provides the basis for fostering and sustaining population development. Infrastructure generally means the roads, bridges, sewers, water systems, rail systems, and mass transit which routinely supply services to the urbanized population of the United States. A critical portion of this infrastructure development is the planning, design and construction of water supply systems.

Water systems generally have high fixed costs and are installed for long design periods. Often water supply facilities are installed with substantial initial excess capacity, which makes the service area attractive for development. The treatment and delivery functions of a water utility represent large economic investments, but the vast

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majority of expenditures are in the delivery system. Population projections made in designing water systems frequently become self-fulfilling. The water utility plays a significant role in community public health and can also become a determinant of the communities' growth path.

Traditional thinking in water supply, and in civil engineering, seldom considers location as a specific factor in engineering analysis. Normally, spatial location and relationships are considered incidental, which is suprising since many engineering activities deal with the design, construction and provision of services over geographically diverse locations. Properly defined spatial analysis can contribute another variable that allows for more complete analyses and definition of system performance.

Recently in water supply engineering there has been a growing interest and awareness of the use of spatial analysis and a formal consideration of spatial variations. Many researchers, consultants, planners and implementers have come to recognize that geographic location is a common denominator, linking nearly all planning and engineering data and provides the basis for timely storage, retrieval and manipulation of data base information, relating to property ownership and assessment, easements, zoning restrictions, permits, utilities, transportation and environmental data, housing, schools, land use, soils, natural resources, crime, fire, etc.

The majority of the spatial considerations that relate directly to water supply systems are associated with distribution design and operation. These aspects of spatial analysis along with examples of completed and ongoing research being conducted by EPA will be discussed in the following sections. Another use of spatial analysis is in water resources where there is concern for relating industrial and nonpoint source discharges to influent water quality. Ongoing work in this area will also be discussed.

SPATIAL ANALYSIS AND WATER DISTRIBUTION SYSTEMS

Design of water distribution systems can be divided into four major areas. The first is concerned with basic land use and demographic parameters used to determine the preliminary size and shape of the service area. The second area of concern reflects the natural features of the service area. The third area of concern is the capacity requirement of the system as a whole and that of individual components. The fourth area of concern is that of engineering design criteria, such as the diameter of pipe, the minimum and maximum velocities, minimum and maximum slopes, and the flow characteristics of the pipes themselves.(4,10)

The nature, quantity and locations of water demand can be determined by using spatial analysis as an organizing factor. These demands can also be determined over time. Once temporally and spatially varying demands have been established, only then can capacity limitations and design of the various components of the system be determined. An example of this approach has been developed for the Washington Metropolitan Area.(5)

SPATIAL COSTING AND ECONOMICS

The early studies that utilized spatial variation as a key factor in water supply system performance were a series of case studies conducted at various utilities together with an in-depth economic evaluation using the Cincinnati Water Works as a source of data.[1] This in-depth study incorporated the use of planning permits, zoning and marginal cost economics as a means of both planning for future capacity expansion and establishing equitable rates.[7]

In the first series of case studies the waterworks were subdivided into various zones, and then incremental costs were collected for the zones in an attempt to gain insights as to how costs change as water moves from the central treatment plant to the various water demand points within the system. These case studies provided an empirical basis for development of a spatially oriented cost analysis system.

This concept provides for allocation of costs, not only to the specific functions of acquisition, treatment or delivery, but also to the subfunction level as illustrated in Figure 1. Two types of costs were identified. Those associated directly with the operating functions of acquisition, treatment and delivery just described, and those not identified with any specific operating function. This second type includes billing, accounting and management, and was placed in a separate category called support services. Figure 1 shows these costs distributed across the entire utility operation. The cost categories which would normally be the cost items included in the utilities charts of accounts can be cross-referenced against

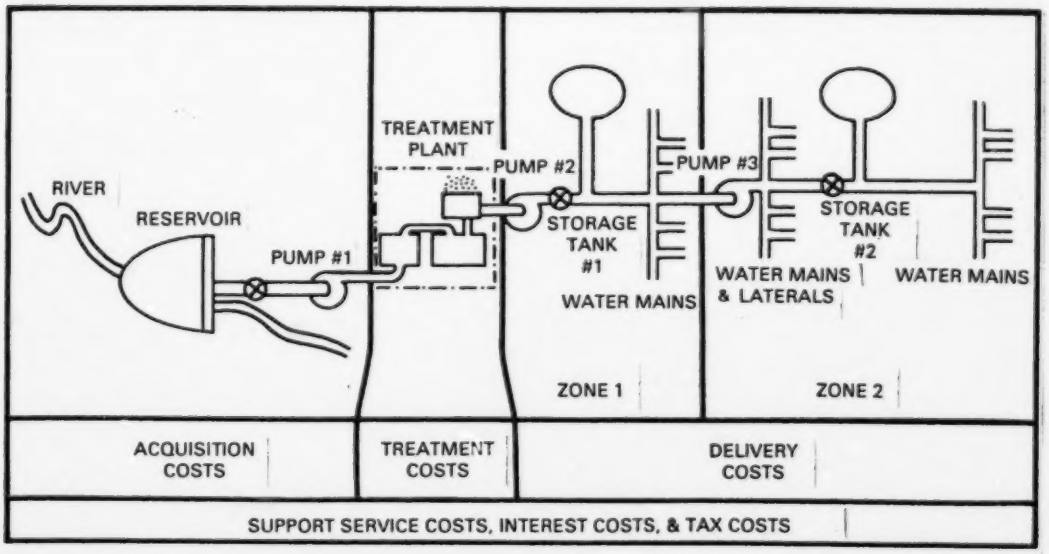

Figure 1. Water utility simplified schematic.

the utilities functions. Documentation of costs in this format makes it possible to retrieve and display the various levels, or types of information desired. This concept was implemented as a spatial costing system in two water systems. The second example involves development of a more formal analytical approach to evaluating the impact of population density on the cost of water supply. Using this approach the water supply system was separated into two components, the treatment plant and the delivery or the transmission and distribution systems, and it was postulated that each of these components had a different cost function. In the case of the water treatment facility, the unit costs tended to decrease as the quantity of service provided increased. But the delivery system was more directly affected by the characteristics of the area being served. It was hypothesized that the cost tradeoffs between the two components will determine the least-cost service area. Figure 2 illustrates this concept. One can see from the average cost curve in Figure 2 the declining average costs due to the economies of scale in treatment and then the rising average costs as the diseconomies associated with the distribution system predominate.(2)

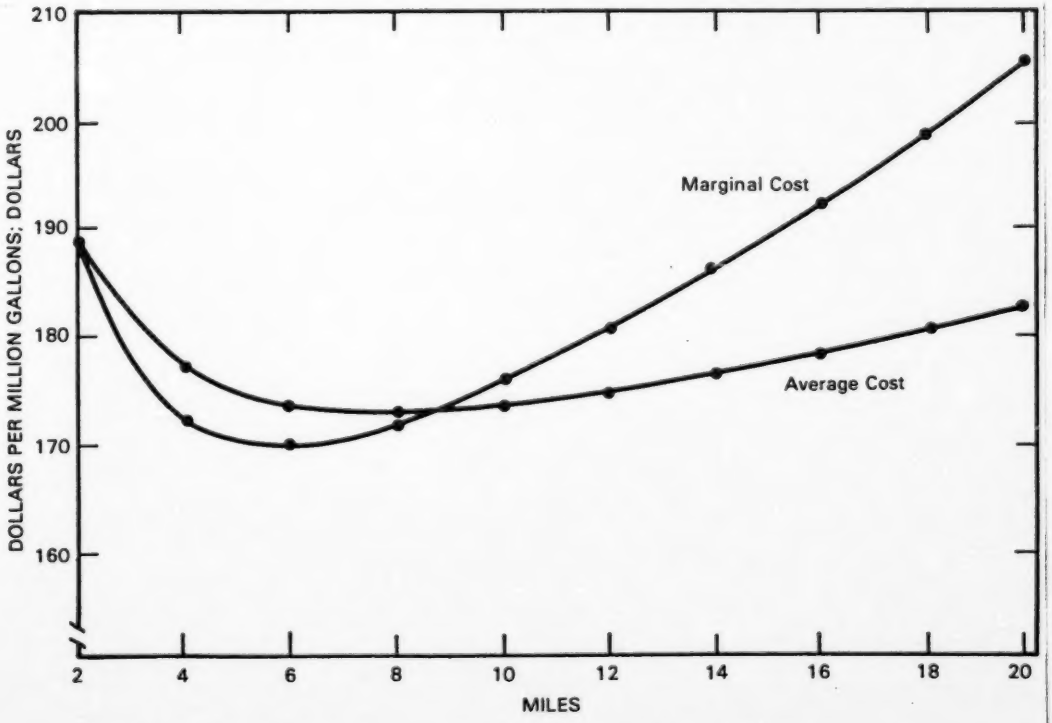

Figure 2. Unit and marginal cost with distance using 150 gal/cap/day.

A major effort to develop a formal tool to analyze the various factors influencing the cost of water supply was undertaken resulting in the development of a Water Supply Simulation Model (WSSM).

WATER SUPPLY SIMULATION MODEL

The WSSM is based upon the concept of a water utility as a network overlaid upon a spatial distribution of supply and demand. The model explicitly deals with the relationship of delivered water costs to the service requirements of spatially and temporally distributed demand. This spatial representation is based on a characterization of the water supply system as a link-node network. It is assumed that water enters and leaves the system only at nodes, which represent treatment plants, junctions, demand locations, and storage tanks. Water is carried between and among nodes through connecting links. Costs are allocated to the various facilities and system components based on flow in the system.(6)

The WSSM requires that the system be described as a network of pipes, storage tanks, treatment plants, demands and other hydraulic elements. Information concerning the network is stored in a network data base, which also stores additional descriptive or calculated information about each element, such as size of pipe, geographic location of each demand often using state plane coordinates, population associated with a demand, connectivity of pipes, etc. Certain basic information must be stored, in order for the system to operate, but other information is elective, and is a function of the particular uses and analysis to which the WSSM is to be put. Other program modules communicate with the data base through standardized data base access methods, which consist of routines to extract or insert information into the network data base.

The two key modules in terms of system evaluation are the hydraulic and solver alogorithms. The current version of WSSM uses both WATSIM and the "Wood Model" as the basis for hydraulic analysis. Both of these algorithms are standards available in the profession and are described elsewhere. The second module SOLVER is a general purpose algorithm that sets up and solves problems relating to mixing in networks, given the network topology and flows.(9) It is used with WSSM for three generic types of problems: (1) determining time required to travel from any source to a node (travel time); (2) determining the concentration of any constituent at any node, given the concentration of the constituent at all sources, and (3) determination of the cost of delivered water at any node, given the individual annualized costs associated with the nodes and links of the system. Ultimately a major objection of the model will be to generate spatial cost variations over the utilities service area as shown in Figure 3.

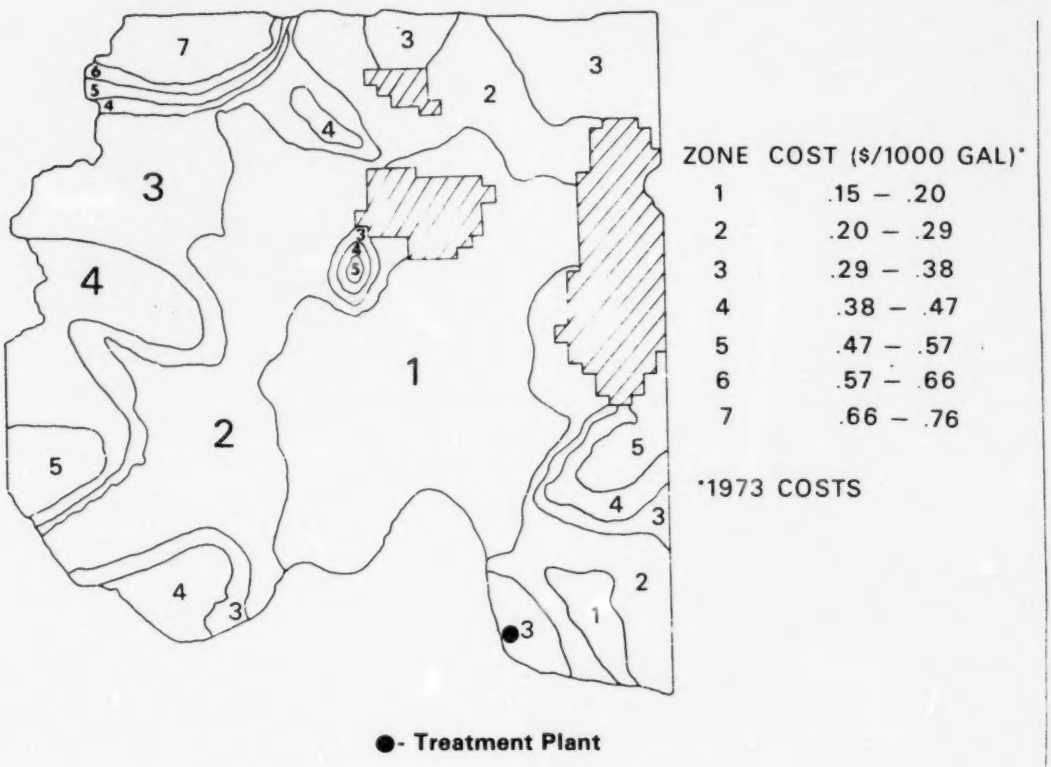

Figure 3. Cost contours for Cincinnati Water Works area, based upon Water Works area, based upon Water Supply Simulation Model.

EXTENSIONS OF MODEL

Currently the use of the WSSM is being extended to test its ability to predict water quality at various locations in a water distribution system. A study is being conducted at the North Penn Water Utility north of Philadelphia to evaluate this concept.

NETWORK RELIABILITY

Research is also being conducted to more fully understand maintenance and repair information for the water supply distribution network. The key to drinking water supply delivery analysis is the performance of reliability assessments. The critical component of an inventory and water main condition assessment is the geo-spatial coding of data, thus providing a common reference system. The Louisville, Kentucky and Cincinnati, Ohio Water Works are undertaking projects which include (1) an overall description of the system (connectivity, physical characteristics, etc.), (2) structural integrity, (3) quality of service and level of usage, and (4) safety. Each link, node, break and customer complaint can be uniquely identified by its location either in State Plane Coordinates and/or the United States Bureau of Census Dime File code. In this manner, a variety of data such as soil type, land use, traffic load, operating pressure, elevation, etc., can be accessed. Hydraulic analyses using

the WSSM or the "Wood Model" can also be integrated into the framework since the network is already specified. Thus, "reliability" analyses need no longer be simply simulations calculated by a hydraulic model, but can also incorporate socio-economic variables. The ability of a utility to anticipate, detect, repair, rehabilitate, reconstruct or replace water supply delivery components is enhanced by the geo-spatial coding of data which provides a common reference system.

TOXIC SCREEING MODELS FOR WATER SUPPLY

Another more general study incorporating the concepts of spatial analysis has been a study conducted to predict toxic waste concentrations in community water supplies along the Ohio and Kanawha Rivers between Charleston, W. Va., and Cincinnati, Ohio, using a water quality simulation model.(8) The project used a case study approach to answer the following questions:

- Are those utilities within a specified number of miles downstream from industrical discharges vulnerable to synthetic organic contamination and subject to EPA's TTHM regulation?

- Should utilities be granted a variance from the regulation if fewer than a certain number of discharges exist upstream from its intakes?

The project also sought to close the gap that potentially exists in the loop between water pollution control and water treatment.

Through the use of the methodology developed, the study predicted which communities in the case study area would be vulnerable to background levels of typical daily discharges. Thus, this study described who is at risk, their relative levels of risk, and the main factors contributing to the risk.

QUAL-II, a water quality simulation model, was used to bring together the diverse elements of mathematical modeling, fluid dynamics, organic chemistry, and geography to create an interactive systems analysis approach that can have an impact of public policy in drinking water. Though QUAL-II is less flexible than other models in simulating various flow scenarios and less sophisticated in modeling dozens of built-in parameters and biological and chemical transformations, the model exhibits a spatial organization that simplifies thinking and highlights critical variables such as the relative locations of utilities and dischargers and the time of travel.

Figure 4 schematically represents the waste loads, tributaries, and junctions involved in the water quality modeling. The contaminants were routed approximately 200 (322 km) miles at various flow scenarios to account for seasonal variations in flow. The next step in the analysis was to develop an inventory and description of existing point sources and communities along the two rivers. To simplify the project, no attempt was made to identify nonpoint sources. Only industrial discharges were considered.

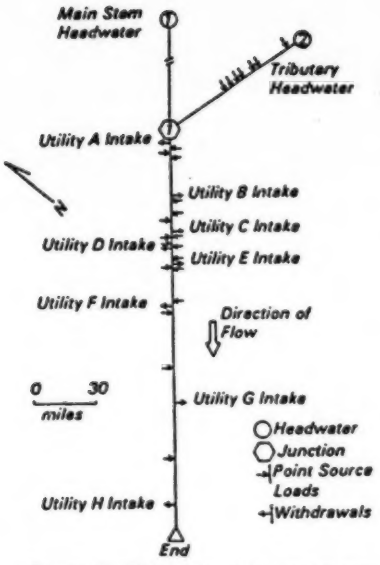

Figure 4. Schematic of the study area

To assess the potential impact on public health, simulated pollutant concentrations for each utility were compared with Water Quality Criteria, which suggest the concentrations of various pollutants that could be harmful to human health. The criteria take into account toxicity, carcinogenicity, or organolepticity (taste and odor) of the pollutants.

For toxic and organoleptic pollutants, the flow is critical in determining whether a Water Quality Criteria has been exceeded. Because vulnerability to carcinogens is evaluated over years of exposure to pollutants in the drinking water, carcinogenic risk levels were initially estimated only at average flows. In the event of a spill, however, the flow characteristics can be important even to carcinogens, since very high concentrations of carbon tetrachloride, for example, can have an acute health effect. Contrary to conventional wisdom, low flows do not necessarily exhibit higher pollutant concentrations than high flows because of decreased dilution. As the volume of water increases, so does the mean velocity in the river channel, thus reducing the time of travel and decay of pollutants. Utilities well downstream can be at higher risk during high flows since the river is bringing the pollutants downstream much quicker and not allowing for decay. Utilities can be vulnerable to different pollutants at different flows.

Analysis of carcinogenic pollutants is done differently than that for the toxic and organoleptic pollutants. Actual health hazards cannot be determined, only risks in terms of expected death rate per pollutant per year can be estimated. Table 1 lists the results of the vulnerability analysis.

TABLE 1

VULNERABILITY OF UTILITIES TO CARCINOGENIC POLLUTANTS AT VARIOUS FLOW RATES

Utility	Expected Death Rate at Average Flow	Expected Death Rate at High Flow	Expected Death Rate at Low Flow
E	6.47(1)*	3.71(1)	19.77(1)
F	5.01(2)	3.14(2)	10.42(2)
G	2.99(3)	2.36(3)	2.35(3)
H	1.57(4)	1.50(4)	0.56(4)
D	0.20(5)	0.13(5)	0.46(5)
B	0.19(6)	0.04(7)	0.44(6)
C	0.18(7)	0.11(6)	0.40(7)
A	0.02(8)	0.01(8)	0.07(8)

*Figures in parentheses indicate ranking.

EXTENSION OF MODEL

The concept developed in the previous section has been extended to the Lower Mississippi in the corridor between New Orelans and Baton Rouge. In this study, data from various EPA and industrial sources is being used to evaluate water quality as it impacts design decisions at the New Orleans water supply intake. In this case the model is being used to structure information needs as they might effect any major water supply using a surface source. The methodologies described can be used to evaluate the tradeoffs that exist between various levels of human exposure to toxic and for carcinogenic chemicals and the cost of water treatment.

SUMMARY AND CONCLUSIONS

Spatial analysis concepts can provide a useful organizing concept for analyzing water supply systems. Examples of the concept applied to design and operation of water distribution systems have been presented.

One set of examples deals with the planning, design and operational aspects of water treatment and delivery. Early studies focused on the allocation of costs to various elements of the water treatment and delivery system. Cost functions were developed for treatment and delivery and a minimum cost point for distribution system size was developed. A tool for formally analyzing the various elements of the water supply system was developed in the Water Supply Simulation Model. The model is based on a link and node (Network) representation of the water supply system. Currently the network concept is being used to integrate maintenance, repair and replacement data for the distribution system with such pieces of information as "colored water reports", break and leak reports", and repair records. These data are being organized according to the network and also geo-coded according to the DIME FILE format.

Another more far reaching example of spatial analysis in water supply is the integration of upstream industrial and toxic dischargers with design decisions in downstream water treatment. The implications for water quality and river basin management are being studied. This approach forces pollution control elements of EPA to recognize their impact on Drinking Water utilities.

The spatial concept in water supply provides a powerful mechanism for analyzing both system and environmental impacts.

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